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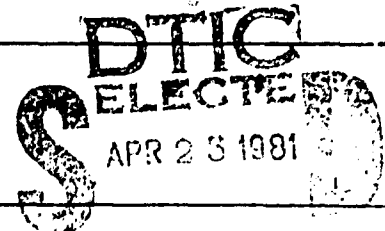
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EROSIVE BURNING OF COMPOSITE SOLID PROPELLANTS*

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ABSTRACT

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The erosive burning characteristics of a series of eight composite solid propellants with systematically varied composition and particle size parameters have been measured over a wide range of pressures and crossflow velocities. Predictions of erosive burning made using a simplified version of a composite propellant erosive burning model based on columnar diffusion flame bending have been found to agree reasonably well with data, except under conditions where the propellant heterogeneity is unimportant. Theory and experiment both indicate an increase in erosion sensitivity with increased pressure over the range of conditions studied. It appears that the dominant factor influencing the sensitivity of composite propellant burning rate to crossflow is the base (no crossflow) burning rate versus pressure behavior of the propellant (lower base burning rate leading to increased crossflow sensitivity), with other factors having at most a second order effect except through their influence on base burning rate. Emphasizing this point, three propellants with widely differing compositional and ingredient particle size parameters, but with essentially the same base burning rate versus pressure relationship, exhibited nearly identical erosive burning characteristics.

INTRODUCTION AND BACKGROUND

Erosive burning, the augmentation of solid propellant burning rate by the flow of products across a burning surface, is becoming increasingly important with use of lower port-to-throat area ratio motors and nozzleless motors, both of which result in high velocity crossflows. The response of various propellants to such crossflows must be known by the motor designer in order for him to perform adequate motor design. In addition, it is important that the propellant formulator understand the effect of various formulation parameters on the sensitivity of a propellant to crossflows so that he may tailor his propellants to the desired characteristics. For example, in a nozzleless rocket motor, the decrease in pressure from the head end to the aft end of the grain tends to result in slower burning at the aft end in the absence of erosive effects. Depending upon the sensitivity of the formulation to crossflow, the increasing Mach Number along the grain port may lead to undercompensation, exact

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cancellation, or overcompensation of the pressure effect. A detailed discussion of the effects of erosive burning on solid propellant rocket interior ballistics for low port-to-throat area ratio motors and nozzleless motors along with a description of the state-of-the-art as regards experimental and modeling studies of erosive burning as of 1976 was presented by this author in Ref. 1.

In the current Atlantic Research program on which this paper is based, the erosive burning of composite solid propellants is being experimentally and analytically studied. The program includes: (1) development of a simplified (Generation 1) model for prediction of erosive burning of a composite propellant, given the non-erosive burning rate-pressure relationship for that formulation; (2) development of a more fundamental (Generation 2) composite propellant combustion model for prediction of burning rate as a function of pressure and crossflow velocity (including prediction of the no-crossflow burning rate-pressure relationship) given only the propellant composition and particle size distributions for the various solid ingredients; and, (3) experimental measurement of the erosive burning characteristics (at crossflow velocities up to Mach 1) of a series of propellants with systematically varied compositions and ingredient particle sizes. The simplified first generation model has been described in detail in References 2 and 3. The more sophisticated second generation model is still under development: a preliminary description of this model appears in Ref. 4, and a more complete description of this model, with comparison between data and theory will be presented in Ref. 5. The major objectives of this paper are presentation of erosive burning data obtained to date on this program, comparison of the data with predictions made with the first generation model, and definition of parameters having major effects on the sensitivity of composite propellant burning rate to crossflow.

First, however, a brief discussion aimed at clearing up an apparent misunderstanding regarding the proposed composite propellant erosive burning mechanism utilized in both the first and second generation models will be presented. As explained in detail in References 2 - 4, the mechanism by which crossflow is proposed by this author to affect the burning rate of composite propellants involves the shortening of the distance (measured normal to the surface) associated with the mixing of the columns of fuel and oxidizer gas leaving the surface. It must be emphasized that this model is meant to apply only to composite propellants in which there is significant heat release associated with reaction between fuel and oxidizer decomposition products. Other mechanisms must be invoked to explain the erosive burning of homogeneous propellants (or HMX-oxidized composites, which do not have a significant O/F flame). In addition, it should be pointed out that other modelers propose alternate erosive burning mechanisms for not only homogeneous propellants, but composite propellants as well. With most of the other modern models, it is concluded that crossflow-induced turbulence is the major cause of augmented burning, either through the enhancement of species and enthalpy transport properties or via eddy breakup.⁽⁶⁻¹¹⁾ It is the contention of this author, however,

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that for composite propellants the flame offset distances are sufficiently small that the flames driving the propellant combustion lie inside a laminar sublayer and thus are unaffected by crossflow-induced turbulence, except through the effect of this turbulence on the overall boundary layer flow profile. (For homogeneous propellants, on the other hand, it is generally conceded that flame offset distances are much larger, due to the existence of a long "dark zone" in which free radicals slowly build up to a critical concentration: accordingly, it is felt by this author that crossflow-induced turbulence may well be important in the erosive burning of these propellants.) This point is discussed in more detail in References 3 and 12.

At any rate, the mechanism proposed by this author for augmentation of the burning rate of composite propellants by crossflow is based on the shortening of the oxidizer gas-fuel gas mixing distance (measured normal to the surface) resulting from the "pushing over" of the oxidizer and fuel gas columns by the crossflow. In References 2-4, this author stated that it could be shown through geometrical arguments coupled with the columnar diffusion flame height analysis of Schultz, Penner, and Green⁽¹³⁾ that the magnitude of the mixing distance (referred to in these papers as L_{diff} or FH90) measured along a vector coincident with the resultant of the crossflow and transpiration velocities should be approximately the same as the mixing distance measured normal to the surface in the absence of a crossflow at the same burning rate and pressure, thus resulting in a decrease in the distance component normal to the surface with crossflow. Discussions with other composite propellant combustion modelers have indicated that it was not made obvious in these references how this conclusion was reached without recourse to use of turbulence-augmented transport properties. Accordingly a simplified version of the analysis used in reaching this conclusion is presented in Figure 1, which is essentially self-explanatory. Basically what appears to have worried those questioning the conclusion that the magnitude of L_{diff} measured in the direction of the flow is independent of that direction is that the time required for a parcel leaving the surface to travel the distance L_{diff} in the flow direction θ , at constant burning rate, is inversely proportional to the sine of the flow angle. This is indeed true. However, the characteristic mixing time is also decreased since the average concentration gradient is increased by the circular cross-section (in the absence of crossflow) being converted to an elliptical cross-section with major axis d_p and minor axis $d_p \sin \theta$. Obviously, doing an exact calculation of the effect on characteristic mixing time is somewhat difficult. However, replacement of the circle diameter d_p by the geometric mean ellipse diameter, $\sqrt{d_p^2 \sin \theta}$ in calculating concentration gradients does not seem unreasonable. When this is done, the magnitude of L_{diff} , measured in the flow direction, is calculated to be independent of flow angle, θ , as shown in Figure 1. A somewhat more rigorous (and immensely more complex) analysis has been performed, indicating that the above approximation is quite good for $\theta > 20$ degrees, but that for smaller angles (columns further pushed over) the magnitude of L_{diff} actually begins to decrease relative to the no-crossflow value. The results of this more rigorous calculation have

not been built into either model yet, L_{diff} being assumed to be independent of θ : this modification will probably be made (at least to the second generation model) in the future.

EXPERIMENTAL

EQUIPMENT

The experimental test apparatus and procedures employed in this study of erosive burning are described in detail in Reference 2. A schematic of the basic test apparatus is presented as Figure 2. A cylindrically perforated 604 driver grain (15.2 cm outside diameter, 10.2 cm inside diameter) whose length is chosen to give the desired operating pressure for a given test, produces a high velocity gas flow through a transition section into a rectangular test section which contains the test grain (generally the same formulation as the driver grain). The contoured transition section is approximately 30 cm (4 inches) long. The test grain extends from the test section back through the transition section to butt against the driver grain in order to eliminate leading edge effects which would be associated with a test grain standing alone. The test grain is approximately 30 cm (12 inches) long (plus the 10 cm extending through the transition section) by 1.90 x 2.50 cm (3/4 inch and 1 inch) web and burns only on the 1.90 cm face. The flow channel of the test section is initially 1.90 cm x 1.90 cm (3/4 inch x 3/4 inch), opening up to 1.90 cm x 4.45 cm (3/4 inch x 1-3/4 inch) as the test propellant burns back through its 2.54 cm (1 inch) web. For high Mach number tests, the apparatus is operated in a nozzleless mode with the gases choking at or near the end of the test grain, while for lower Mach Number tests, a 2-dimensional nozzle is installed at the end of the test channel.

During each test, pressure and crossflow velocity varies with time and location along the test grain. (For the nozzleless tests, pressure varies significantly with time and location, while crossflow velocity varies considerably with location but not significantly with time. For tests using a nozzle with an initial port to throat area ratio of 1.5 or higher, on the other hand, pressure does not vary strongly with location but does rise with time due to the progressivity of the driver grain, while crossflow velocity varies strongly with time and slightly with location.) These variations permit design of tests to yield considerable burning rate-pressure-crossflow velocity data in relatively few tests, provided that these parameters can be measured continuously at several locations along the test grain. These parameters are measured in the following manner.

The burning rate is directly measured by photographing the ablating grain with a high-speed motion picture camera through a series of four quartz windows located along the length of the test section. Frame by frame analysis of the films permits determination of instantaneous burning rate as a function of time at each of the four window locations.

For nozzled cases, the measured location of the burning propellant surface at each window as a function of time, together with the known

constant throat area, permits straightforward calculation of the cross-flow velocity as a function of time. However, the very sensitive dependence of Mach Number on area ratio for $M > 0.5$ makes calculation of cross-flow velocity from area ratio measurement quite poor for nozzleless cases. Accordingly, for these tests, stagnation pressure is determined at the aft end of the test section and used in combination with the driver chamber pressure for calculation of the stagnation pressure in the test section as a function of time and position. Static pressure wall taps at each window location are used for measurement of static pressure as a function of time for both nozzled and nozzleless cases. From the static and stagnation pressure values determined as a function of time and position down the test section, crossflow Mach Number and velocity are calculated as a function of time at each window location in the test section for the nozzleless cases.

TEST MATRIX

The purpose of the experimental part of this program is to characterize, over a wide range of pressure and crossflow velocity, the erosive burning behavior of a series of propellants in which various formulation parameters are systematically varied. To date, the eight formulations listed in Table I have been studied. The first five of these formulations, as indicated, contained unimodal oxidizer. It was considered important

Table I. Formulations Tested

<u>Designation</u>	<u>Composition</u>	<u>Selection Rationale</u>
1. (4525)	73/27 AP/HTPB, 20 μ AP	Baseline Formulation, $T = 1667^\circ\text{K}$
2. (5051)	73/27 AP/HTPB, 200 μ AP	Compare with 1 for AP size effect
3. (4685)	73/27 AP/HTPB, 5 μ AP	Compare with 1 and 2 for AP size effect
4. (4869)	72/26/2 AP/HTPB/ Fe_2O_3 , 20 μ AP	Compare with 1 for effect of base burning rate at constant AP size
5. (5542)	77/23 AP/HTPB, 20 μ AP	Compare with 1 for mix ratio (temperature) effect at constant AP size. $T = 2065^\circ\text{K}$
7. (5565T)	82/18 AP/HTPB, Bimodal AP (68.35% 20 μ , 13.65% 90 μ)	Medium temperature formulation (2575°K). AP sizes chosen to give same base burning rate characteristics as 1. Compare with 1 for temperature effect.
8. (5555T)	82/18 AP/HTPB, Bimodal AP (41% 1 μ , 41% 7 μ)	Compare with 7 for effect of base burning rate.
11. (6626)	74/21/5 AP/HTPB/Al, Bimodal AP (70% 90 μ , 4% 200 μ) 6 μ Al	AP sizes chosen to match base burning characteristics of 1 and 7. $T=2460^\circ\text{K}$ (nearly equal to that of 7). Compare with 7 for aluminum effect.

that initial tests be carried out with such formulations for definition of oxidizer particle size effects under "clean" conditions. In addition, the second generation model was originally developed for unimodal oxidizer

formulations (with later extension to multimodal oxidizer cases): accordingly, these initial tests were important for testing and modification of the basic unit model. Formulation 1 (4525) was selected as a baseline HTPB/AP composite propellant. Formulations 2, 3, and 4 (5051, 4685, 4869) represent simple variations from the first formulation aimed at permitting isolation of the effects of oxidizer particle size and base burning rate on crossflow sensitivity, as discussed further below.

In terms of independent variables, Formulation 5 (5542T) differs from the baseline formulation only in oxidizer/fuel ratio. Due to this difference, of course, the flame temperatures differ and, because AP size is held constant, the base burning rate characteristics differ (Formulation 5 having a higher base burning rate). Thus, comparison of the results for these formulations permits definition of the effect of oxidizer/fuel ratio change at constant oxidizer particle size. With Formulation 7 (5565T) on the other hand, oxidizer/fuel ratio is varied from that of Formulation 1, but oxidizer particle sizes are adjusted in Formulation 7 to give approximately the same zero-crossflow burning rate characteristics for the two formulations, permitting examination of the effect of varying oxidizer/fuel ratio at constant base burning rate. Formulation 8 (5555T) is identical to Formulation 7, except for use of much finer oxidizer sizes to yield higher base burning rate, permitting further study of the affect of this parameter on erosion sensitivity. Formulation 11 (6626) is the first metalized propellant studied. This composition was chosen to give approximately the same flame temperature as Formulation 7, while the oxidizer size was adjusted to give approximately the same base burning rate versus pressure curve as obtained with Formulations 1 and 7, allowing determination of any direct affect of aluminum on erosive burning sensitivity.

RESULTS AND COMPARISON TO THEORY

Two matched pairs of tests, with test conditions being held nearly identical from test to test within each pair except for the presence or absence of a test grain extension through the transition section (providing a smooth transition from the driver grain surface to the test grain surface) were conducted to determine whether the erosive burning rate in the test section was unduly sensitive to upstream hydrodynamic conditions. The results of these tests are presented in Figures 3 and 4, along with predictions made with the first generation model mentioned earlier. (These are included to permit zeroing out of slight differences in pressure and crossflow velocity versus time histories in the paired tests.) As may be seen, the effects of upstream flow changes were quite small, with the differences in burning rate augmentation ratio between corresponding tests occurring essentially only to the degree predicted by the slight difference in pressure-crossflow velocity-time history in the matched tests. Accordingly, it is concluded that the erosive burning measured at the viewing ports is not particularly sensitive to the driver grain-transition section contours in the test apparatus. This result is consistent with an observation that the augmentation rates do not vary significantly with window location for the nozzled tests (where pressure and crossflow velocity are nearly the same at each window location at any given time).

As discussed in References 1 - 3, there are a number of erosive burning models based on increased heat transfer from a "core" gas flow (notably the widely used model of Lenoir and Robillard⁽¹⁴⁾). If this is indeed the controlling mechanism, one would predict that with a given test section propellant, variation of the flame temperature of the driver propellant should lead to variation in the erosive burning augmentation ratio at fixed crossflow velocity and pressure. Two matched pairs of tests (1 and 9, 3 and 10), in which the driver grain flame temperature was varied from 1667°K to 2425°K, while the test section propellant was held constant and crossflow velocity and pressure versus time histories were kept as nearly equal as possible, were carried out in the course of this study to test this hypothesis. The Lenoir and Robillard model predicts approximately 50 percent higher augmentation ratio with the hotter driver grain than the cooler one. The results of these tests, presented in Figures 5 and 6 (again with first generation model predictions to permit zeroing out of pressure and crossflow velocity differences between tests) indicate negligible effect of "core" gas temperature on the erosive burning characteristics of the test propellant, casting serious doubts on the Lenoir and Robillard type models.

A rather complete set of data, covering a pressure range of 1 to 5 MPa (10 to 50 atmospheres) and a crossflow velocity range of 180 to 670 m/sec (600 to 2200 ft/sec) has been obtained for Formulation 4525, the baseline formulation. Experimental results and theoretical predictions (based on the first generation model mentioned earlier) are presented in Figures 7 and 8. As may be seen, agreement between predictions and data is reasonably good. The predicted curves for burning rate versus pressure at various crossflow velocities (Figure 7) do seem to group more tightly than the data. That is, as shown more clearly in Figure 8, the model tends to slightly overpredict the burning rate at low crossflow velocities and slightly underpredict it at high velocities. As with the other propellants studied, theory and data both indicate increasing erosive burning sensitivity with increasing pressure over the range of conditions studied.

Theoretical predictions and experimental measurements of erosive burning rates for Formulations 5051, 4685, 4869, 5542T, 5565T, 5555T, and 6626 are presented in Figures 9 through 15. Formulation 5051, which differs from the baseline formulation through use of 200 micron AP oxidizer in place of 20 micron oxidizer, is predicted to be somewhat more sensitive to crossflow than the baseline formulation. Except at low pressure and very high crossflow velocities, agreement between predicted and measured augmentation ratio is fairly good. At low pressure and high crossflow velocity, however, the measured burning rates considerably exceed the predicted values. As shown in Figure 10, Formulation 4685, which differs from the baseline formulation by replacement of 20 micron oxidizer with 5 micron oxidizer, exhibits considerably less sensitivity to erosion than that baseline formulation, as predicted. Agreement between predicted and observed burning rates appears to be good except, again, in the low pressure, high crossflow velocity region (less than 2 MPa or 20 atmospheres, greater than 300 to 600 m/sec or 1000 to 2000 ft/sec).

crossflow velocity). Breakdown of the model presented herein in this pressure-crossflow velocity region is not unexpected since, in this region, the composite propellant begins to behave more like a homogeneous propellant than a heterogeneous propellant, and the model only considers effects of crossflow on the diffusional mixing processes of oxidizer and fuel streams. In order for the model to be useful in low pressure, high crossflow velocity regions, it appears that an additional mechanism beyond that of flame-bending must be invoked. With Formulation 4869 (Figure 11), which differs from the baseline formulation through addition of two percent iron oxide catalyst, data and theoretical predictions agree fairly well at high crossflow velocities, but not nearly as well at low crossflow velocities where the predictions of erosive burning rate augmentation are somewhat higher than observed in the experiments. An explanation of this discrepancy has not yet been developed.

With Formulation 5542T (analogous to the baseline formulation but with higher oxidizer/fuel ratio and consequently higher temperature and base burning rate, oxidizer size being held constant) the sensitivity to crossflow appears to be somewhat lower than predicted (Figure 12) though the degree of disagreement between data and theory is not large. The data obtained for Formulation 5565T (with approximately the same zero crossflow burning rate-pressure behavior as the baseline formulation, but a considerably higher oxidizer/fuel ratio and flame temperature) presented in Figure 13 indicate reasonable agreement with theory, the formulation being quite sensitive to crossflows. Formulation 5555T (Figure 14), a high burning rate formulation, is predicted to be rather insensitive to crossflows: the data corroborate this prediction.

Predicted and experimental erosive burning characteristics for Formulation 6626, the only metalized formulation tested to date, are presented in Figure 15. Although the data are somewhat sparse, the agreement between experiment and theory appears to be excellent. This is particularly interesting since the first generation flame-bending model used to generate the curves plotted on Figure 15 does not include any specific mechanism involving the aluminum: the excellent agreement with data suggests (though it certainly offers no rigorous proof) that the aluminum, at least at the relatively low level of 5 percent, does not directly affect the erosive burning of composite propellants.

DELINEATION OF FACTORS AFFECTING EROSIVE BURNING SENSITIVITY

Next, let us compare results for the various formulations to identify parameters which influence the sensitivity of composite propellants to crossflows. Between Formulations 4525, 5051, and 4685, the only independent variable changed is the oxidizer particle size. composition being held constant. The change of oxidizer size, of course, leads to a change in base (no crossflow) burning rate versus pressure characteristics. Formulation 5051, containing 200 micron diameter AP, is the slowest burning of the three formulations, with Formulation 4685 (5 micron AP) being the fastest and Formulation 4525 (20 micron AP) being intermediate. For instance, at 5 MPa (50 atmospheres) the base burning rate of 5051 is 0.47 cm/sec, that of 4525 is 0.68 cm/sec and that of 4685 is 1.15 cm/sec.

Examination of Figures 7, 9, and 10 indicates that the sensitivity of burning rate to crossflow increases with increasing particle size (decreasing base burning rate). For example, at a crossflow velocity of 200 m/sec (650 ft/sec) and a pressure of 5 MPa (50 atmospheres), the augmentation ratio for 4685 is about 1.10, that for 4525 is 1.65, and that for 5051 is 2.0.

Comparison of data for 4525 and 4869, two formulations of essentially the same oxidizer/fuel ratio, flame temperature, and oxidizer particle size, with the base burning rate being varied through use of catalyst in 4869, again shows an increase in sensitivity of burning rate to crossflow with a decrease in burning rate. At 5 MPa (50 atmospheres) the base burning rates for 4869 and 4525 are 1.40 cm/sec and 0.68 cm/sec, respectively. At this pressure, with a crossflow velocity of 200 m/sec (650 ft/sec), their r/r_0 values are 1.10 and 1.65 respectively, while at 600 m/sec (1950 ft/sec), the r/r_0 values are 1.75 and 2.3. Thus base burning rate is seen to affect the erosion sensitivity of composite propellants even at constant oxidizer particle size, erosive effects increasing with decreasing base burning rate.

Formulations 4685 and 4869 have approximately the same base burning rate at 8 MPa (80 atmospheres) with catalyst and oxidizer particle size effects on base burning rate roughly cancelling. Thus comparison of erosion sensitivity of these formulations at this pressure is of interest in that oxidizer particle size is varied (5 micron diameter for 4685, 20 micron diameter for 4869) while base burning rate is held constant. Comparison of data from Figures 10 and 11 indicates that these formulations have roughly the same sensitivity to the lower crossflow velocities tested at 8 MPa (80 atmospheres), with the catalyzed propellant being slightly more sensitive at the higher crossflow velocities tested. Thus it appears that it is the base burning rate rather than the oxidizer particle size per se which dominates the sensitivity of composite propellants to erosive burning, though oxidizer size does have some further residual effects, erosion sensitivity decreasing with decreasing particle size at constant base burning rate.

Comparison of test results for Formulations 4525, 5542T and 5565T permits study of the effect of oxidizer/fuel ratio (and thus flame temperature) on erosion sensitivity, both at constant oxidizer particle size (5542T and 4525) and at constant base burning rate (5565T and 4525). Formulation 5542T differed from 4525 in oxidizer/fuel ratio (77/23 versus 73/27) and consequently flame temperature (2065°K vs 1667°K). Since the oxidizer particle size was the same for both propellants, the higher oxidizer/fuel ratio for 5542T led to high base burning rate (1.14 cm/sec vs. 0.68 cm/sec at 5 MPa). Study of Figures 7 and 12 reveals that the erosion sensitivity of 5542T is considerably less than that of 4525 over the entire range of crossflow velocities studied (e.g., $r/r_0 = 1.10$ for 5542T and 1.65 for 4525 at 200 cm/sec, 5 MPa; and $r/r_0 = 1.7$ for 5542T and 2.9 for 4525 at 800 m/sec, 5 MPa). Thus we see that changing oxidizer/fuel ratio from very fuel-rich to less fuel-rich, with accompanying increase in flame temperature and burning rate, leads to decreased sensitivity to erosive burning. Comparison of results for 5565T and 4525, which differ

in oxidizer/fuel ratio but not in base burning rate (oxidizer particle size having been adjusted to compensate for the burning rate change with changing oxidizer/fuel) permits separation of the effects of varying oxidizer/fuel ratio (and thus flame temperature) from the effects of base burning rate. As may be seen by study of Figures 7 and 13, the sensitivity of Formulations 5565T and 4525 to crossflow are nearly the same. For instance, at 200 m/sec (650 ft/sec) crossflow velocity and 5 MPa (50 atmospheres), the augmentation ratios for 5565T and 4525 are 1.50 and 1.65, respectively, while at 800 m/sec (2600 ft/sec) and 3 MPa (30 atmospheres), they are 2.65 and 2.50. Accordingly, we may tentatively conclude that oxidizer/fuel ratio (and consequently flame temperature) does not directly affect the erosion sensitivity of the compositions studied to date, but only affects it through its effect on base burning rate.

Formulations 5555T and 5565T had the same composition, differing only in oxidizer particle size, which was adjusted in 5555T to give a very high burning rate. Again, the effect on erosion sensitivity of increased base burning rate can be seen in comparison of Figures 13 and 14. At 5 MPa (50 atmospheres), the base burning rates of 5555T and 5565T are 2.94 and 0.70 cm/sec, respectively. At 200 m/sec (650 ft/sec) crossflow velocities, the respective values of r/r_0 are 1.0 and 1.5, while at 700 m/sec (2300 ft/sec), they are 1.2 and 2.4. Thus, once again, erosion sensitivity is seen to decrease with increasing base burning rate.

As mentioned earlier, Formulation 6626, the only metalized formulation tested to date, was tailored to have essentially the same base burning rate versus pressure characteristics as Formulations 4525 and 5565 and, moreover, to have approximately the same flame temperature as 5565. It has already been pointed out that comparison of Figures 7 and 13 reveals that Formulations 4525 and 5565 also have nearly identical erosive burning behavior. Comparison of Figure 15 with Figures 7 and 13 reveals further that Formulation 6626 has essentially identical erosive burning behavior as the other two formulations. For example, at a crossflow velocity of 700 m/sec (2300 ft/sec) and a pressure of 2.8 MPa (28 atmospheres) the augmentation ratios for 4525, 5565, and 6626 are 2.05, 2.20, and 2.05; while at 245 m/sec (800 ft/sec) and 4.0 MPa (40 atm), they are 1.80, 1.63, and 1.71. Thus, we are again drawn to a conclusion that the dominant factor affecting the sensitivity of burning rate of a composite propellant to crossflow is the base burning rate, largely independent of the various factors going into determining that base burning rate.

SUMMARY

Eight AP/HTPB composite propellant formulations with systematically varied compositional and particle size characteristics have been characterized with respect to erosive burning over a wide range of pressures and crossflow velocities in a special test apparatus. The erosive burning measurements have been compared with predictions made using a simplified first-generation model based on the bending of columnar diffusion flames by a crossflow. In general, the model gives reasonably good agreement

with data except under conditions where the heterogeneity of the composite propellant is unimportant: here, it appears that an additional erosive burning mechanism will have to be considered. The data obtained to date indicate that the base (no crossflow) burning rate characteristics of the propellant have a predominant affect on its sensitivity to crossflow, high burning rate formulations being considerably less susceptible to erosive burning than low burning rate formulations, whether the base burning rate alterations are produced by oxidizer particle size variation, oxidizer/fuel ratio variation, addition of metal, or use of catalysts. Thus, propellants with widely differing oxidizer size distributions, O/F ratios, metal loadings, etc. tend to show identical erosive burning behavior as long as they have identical base (no crossflow) burning rate characteristics. Oxidizer particle size does appear to have some residual effect (but only a slight one) beyond its effect on base burning rate, erosion sensitivity increasing with increasing particle size. An important preliminary conclusion is that aluminum (at least at low levels) does not affect erosion sensitivity other than through its effect on base burning rate.

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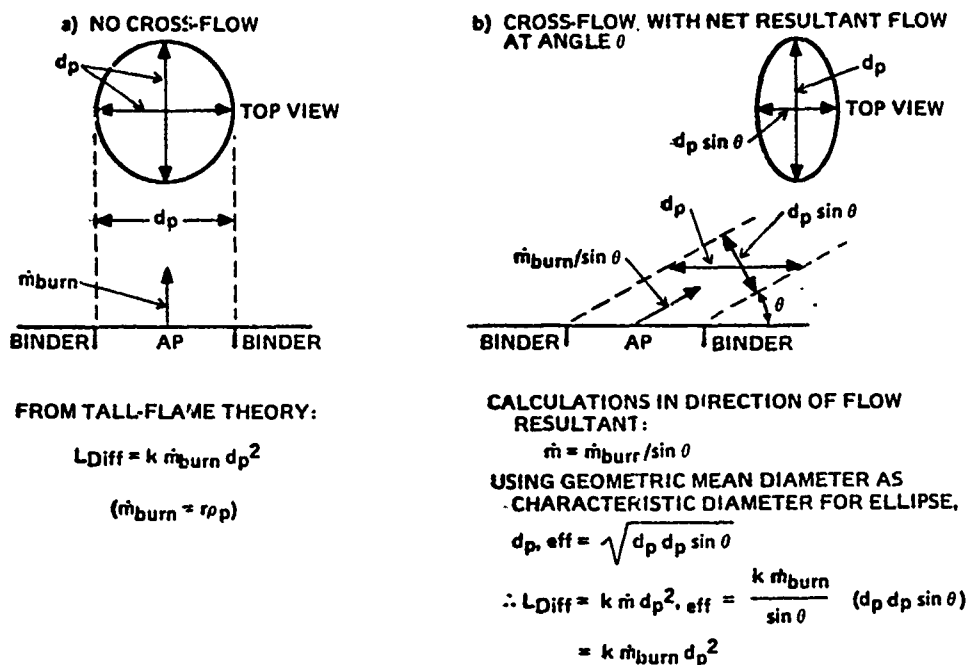


Figure 1. Approximate Calculation of Dependency of Distance Associated with Mixing of Fuel and Oxidizer Streams on Flow Angle, at Fixed Mass Burning Flux.

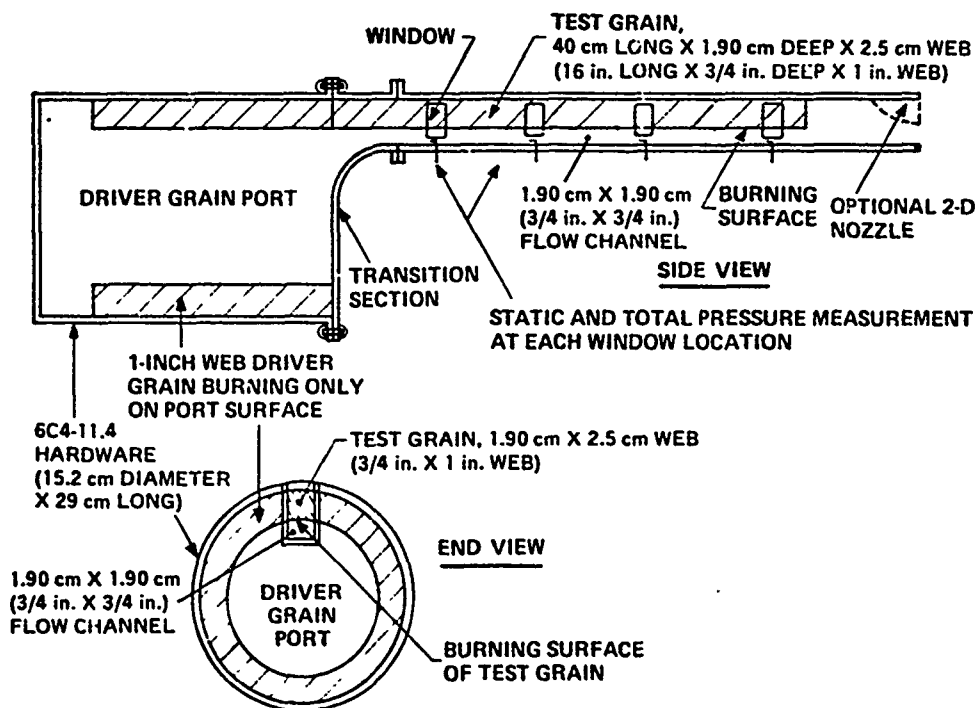


Figure 2. Schematic of Atlantic Research Erosive Burning Test Apparatus.

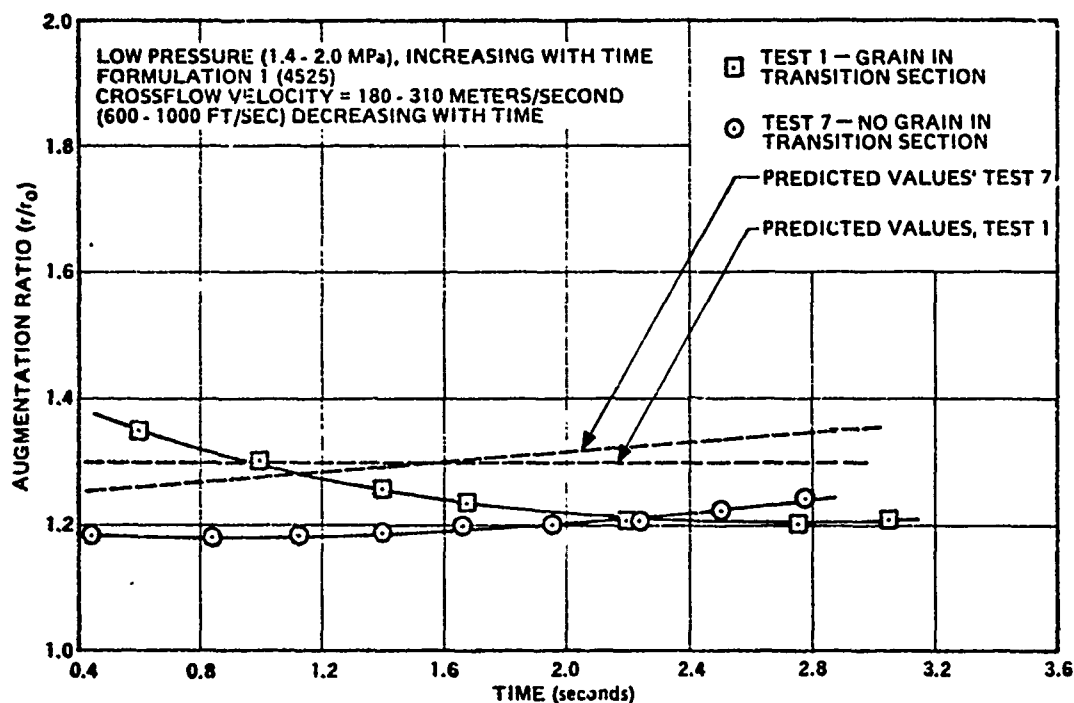


Figure 3. Comparison of Erosive Burning With and Without Test Grain Extending Thru Transition Section to Mate with Driver Grain - Low Pressure.

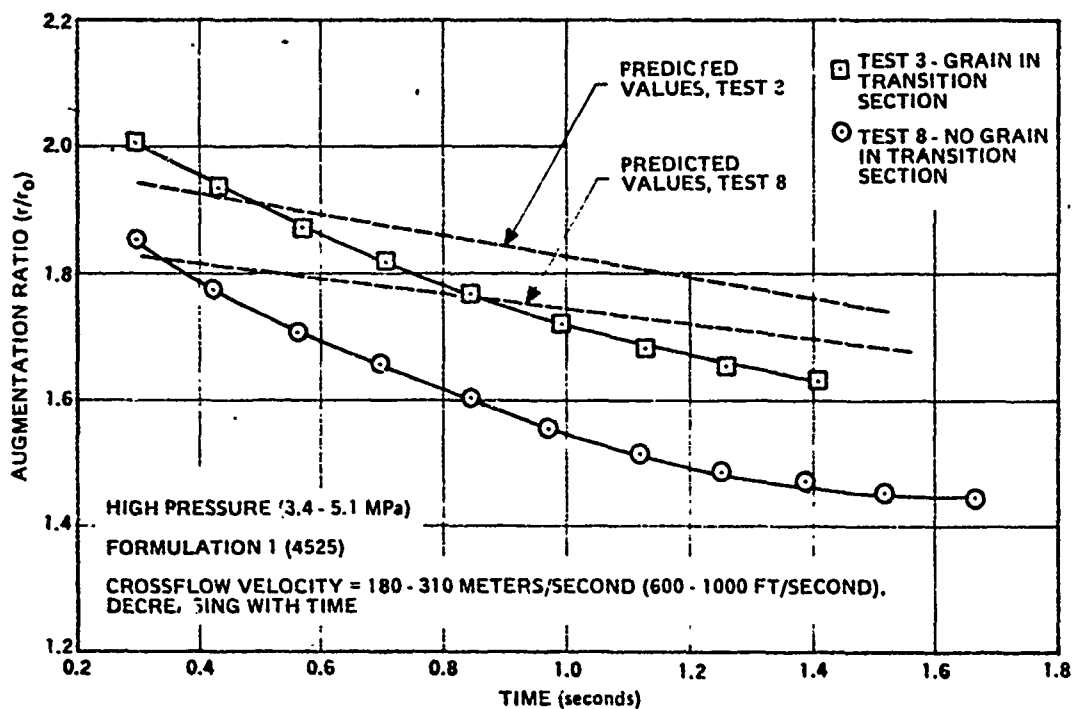


Figure 4. Comparison of Erosive Burning With and Without Test Grain Extending Thru Transition Section to Mate with Driver Grain - High Pressure.

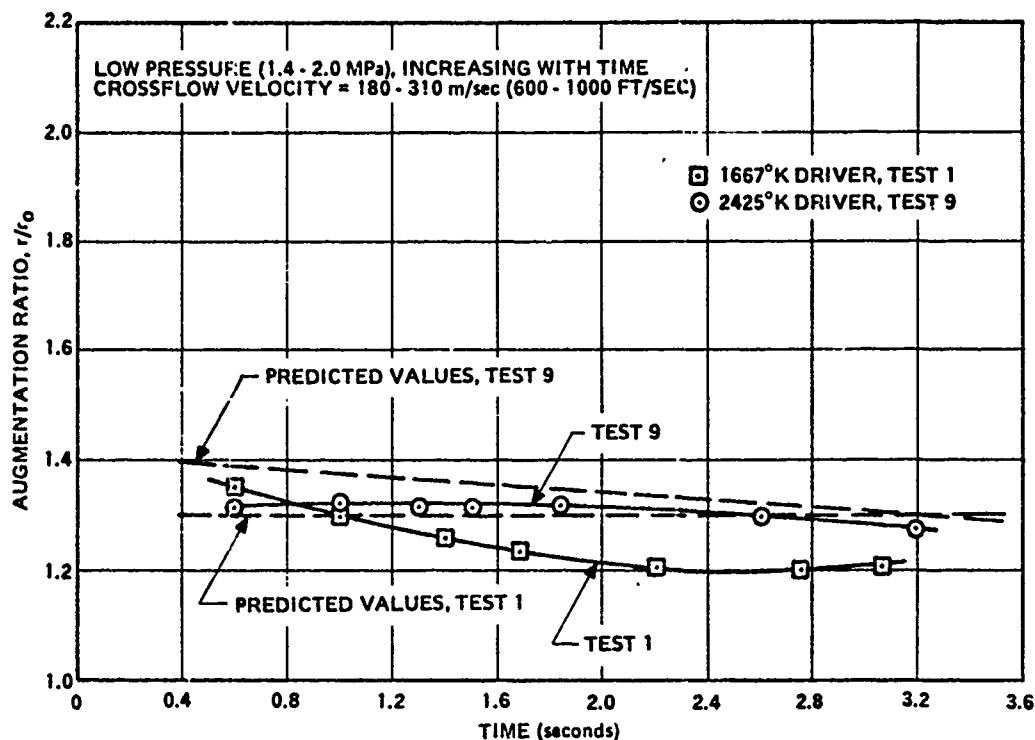


Figure 5. Comparison of Erosive Burning of Formulation 1 (4525) with 1667°K Driver Grain and 2425°K Driver Grain - Low Pressure.

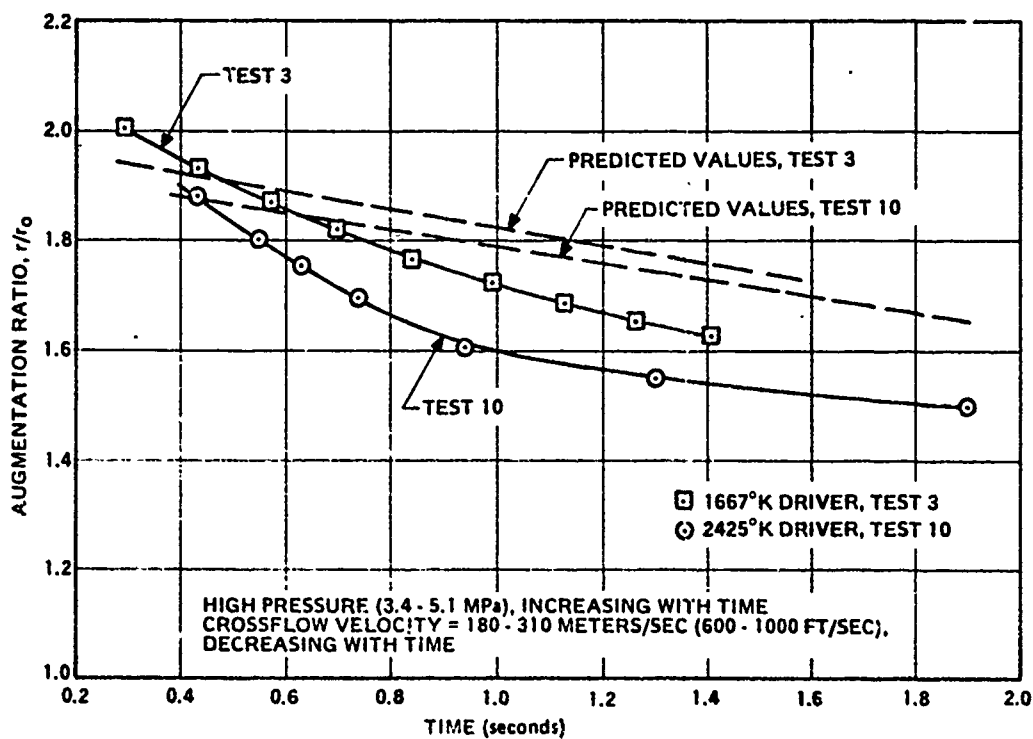


Figure 6. Comparison of Erosive Burning of Formulation 1 (4525) with 1667°K Driver Grain and 2425°K Driver Grain - High Pressure.

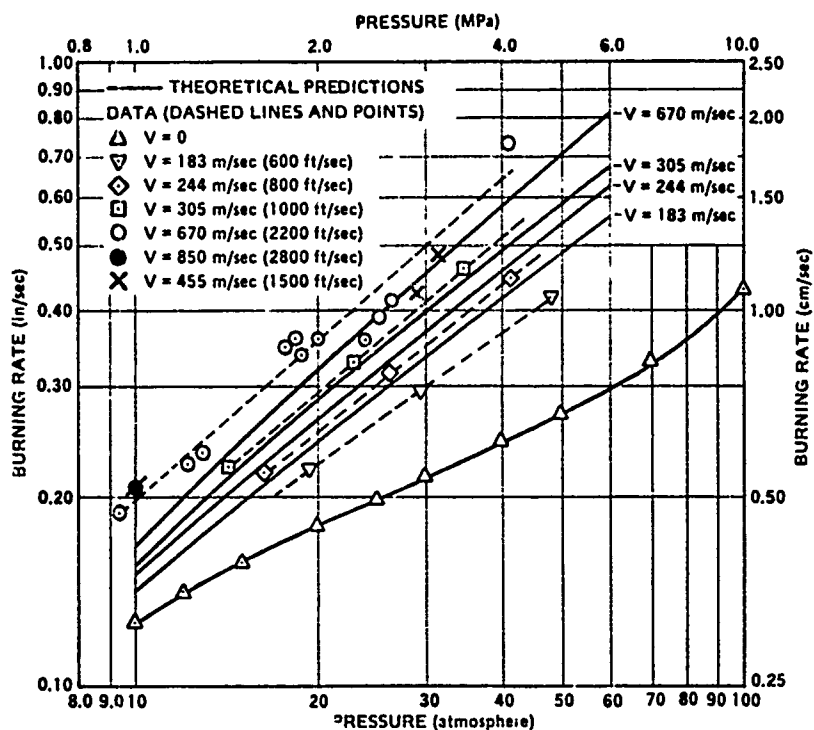


Figure 7. Theoretical and Experimental Burn Rate - Pressure Relationships for Various Crossflow Velocities for Formulation 4525 (1667°K Formulation, 73/27 AP/HTPB, 20 Micron AP).

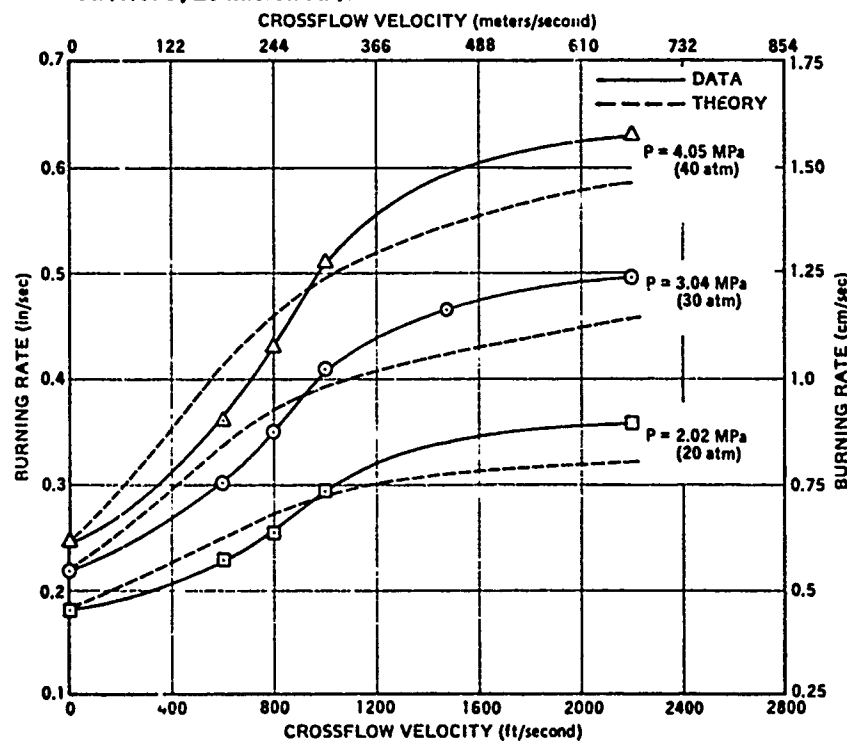


Figure 8. Burning Rate Versus Crossflow Velocity Data and Predictions for Formulation 4525 (73/27 AP/HTPB, 20 Micron AP).

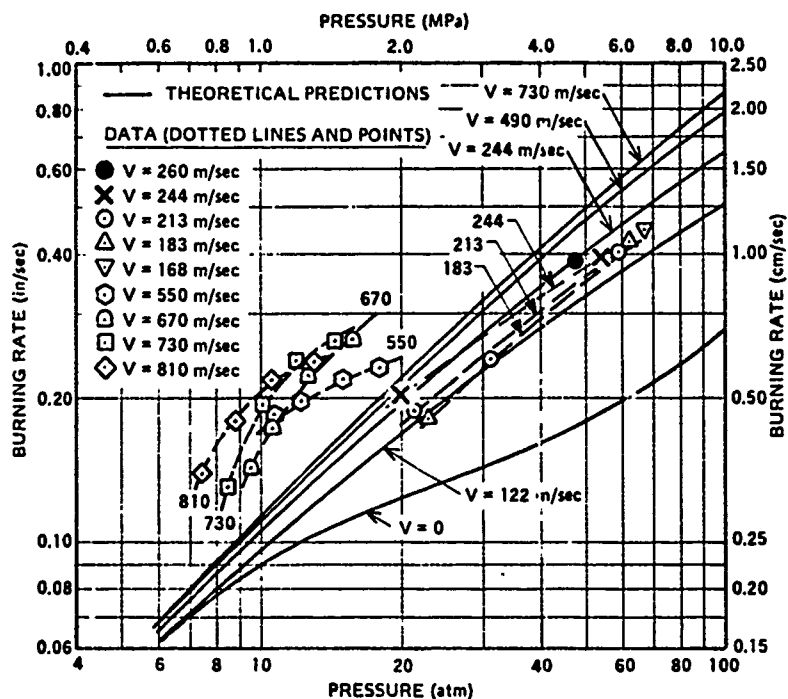


Figure 9. Theoretical and Experimental Burn Rate - Pressure Relationships for Various Crossflow Velocities for Formulation 5051 (1667°K Formulation, 73/27 AP/HTPB, 200 Micron AP).

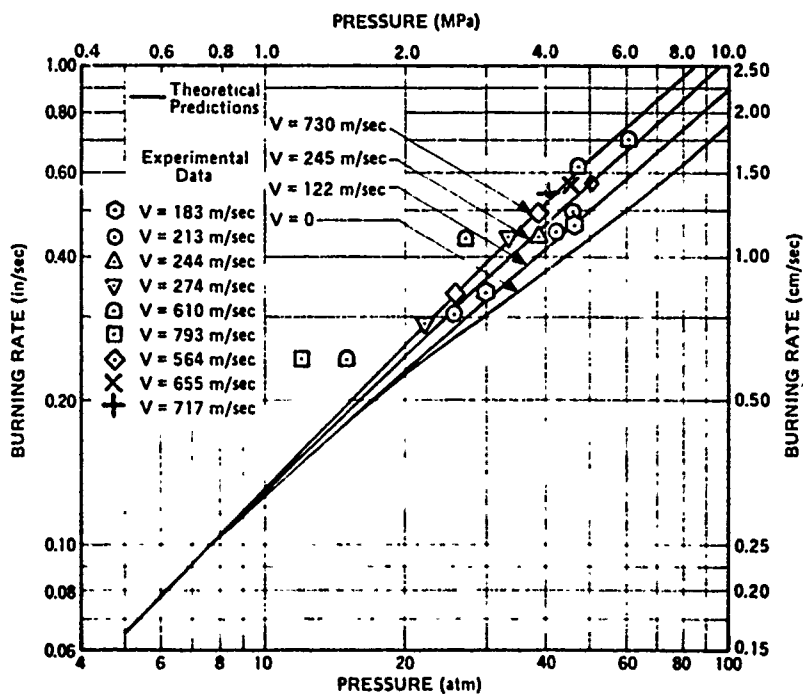


Figure 10. Theoretical and Experimental Burn Rate - Pressure Relationships for Various Crossflow Velocities for Formulation 4685 (1667°K Formulation, 73/27 AP/HTPB, 5 Micron AP).

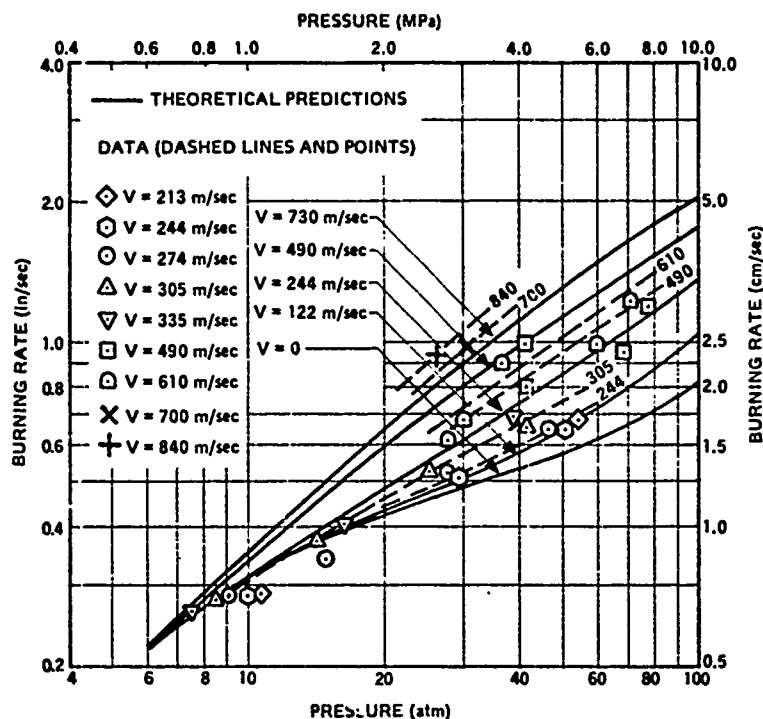


Figure 11. Theoretical and Experimental Burn Rate - Pressure Relationships for Various Crossflow Velocities for Formulation 4869 (1667°K Formulation, 72/25/2 AP/HTPB/ Fe_2O_3 , 20 Micron AP).

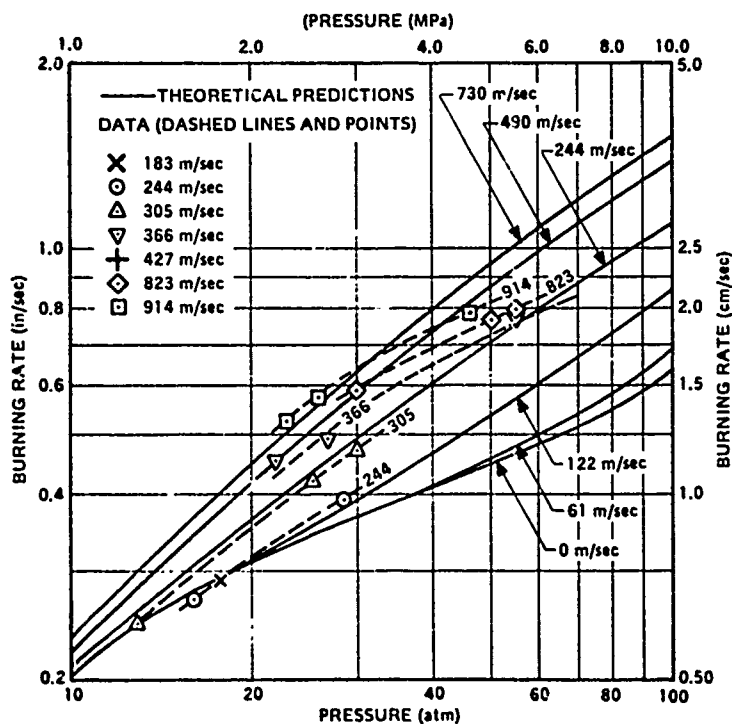


Figure 12. Theoretical and Experimental Burn Rate - Pressure Relationships for Various Crossflow Velocities for Formulation 5542T (2065°K Formulation, 77/23 AP/HTPB, 20 Micron AP).

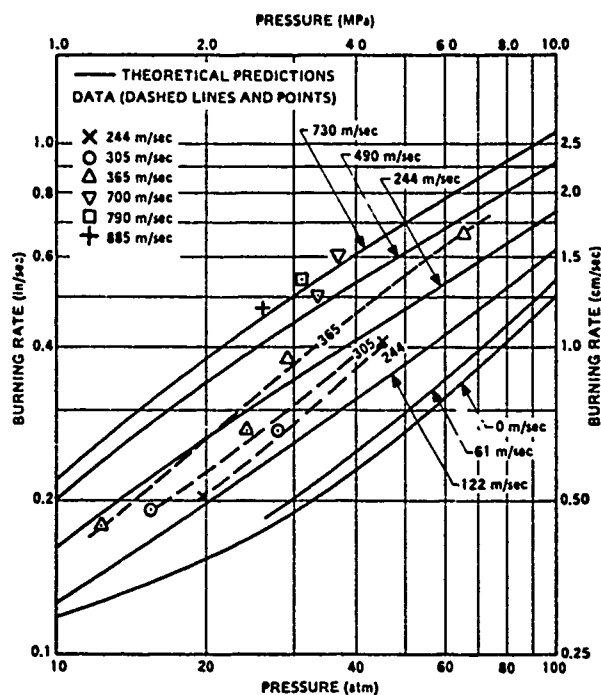


Figure 13. Theoretical and Experimental Burn Rate - Pressure Relationships for Various Crossflow Velocities for Formulation 5565T (2575°K Formulation, 82/18 AP/HTPB, Bimodal with Sizes Chosen to Match 4525 Burning Rate).

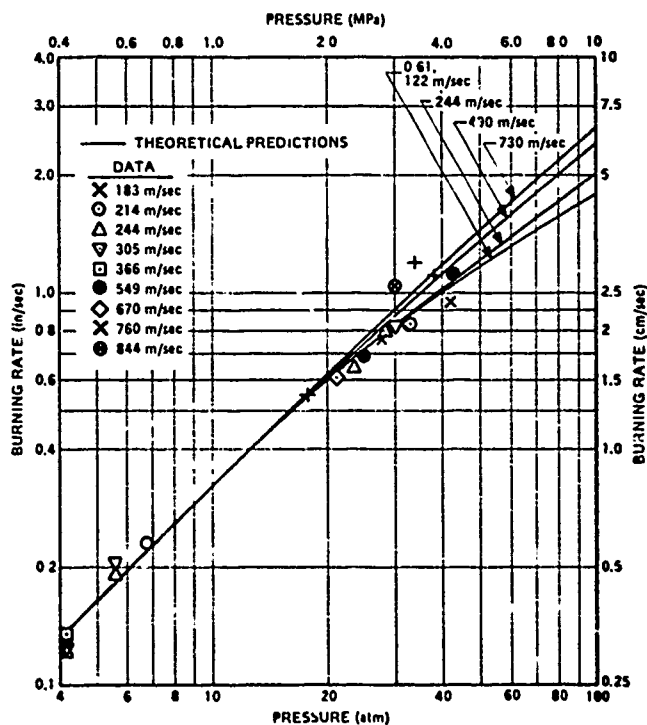


Figure 14. Theoretical and Experimental Burn Rate - Pressure Relationships for Various Crossflow Velocities for Formulation 5555T (2575°K Formulation, 82/18 AP/HTPB, High Burn Rate).

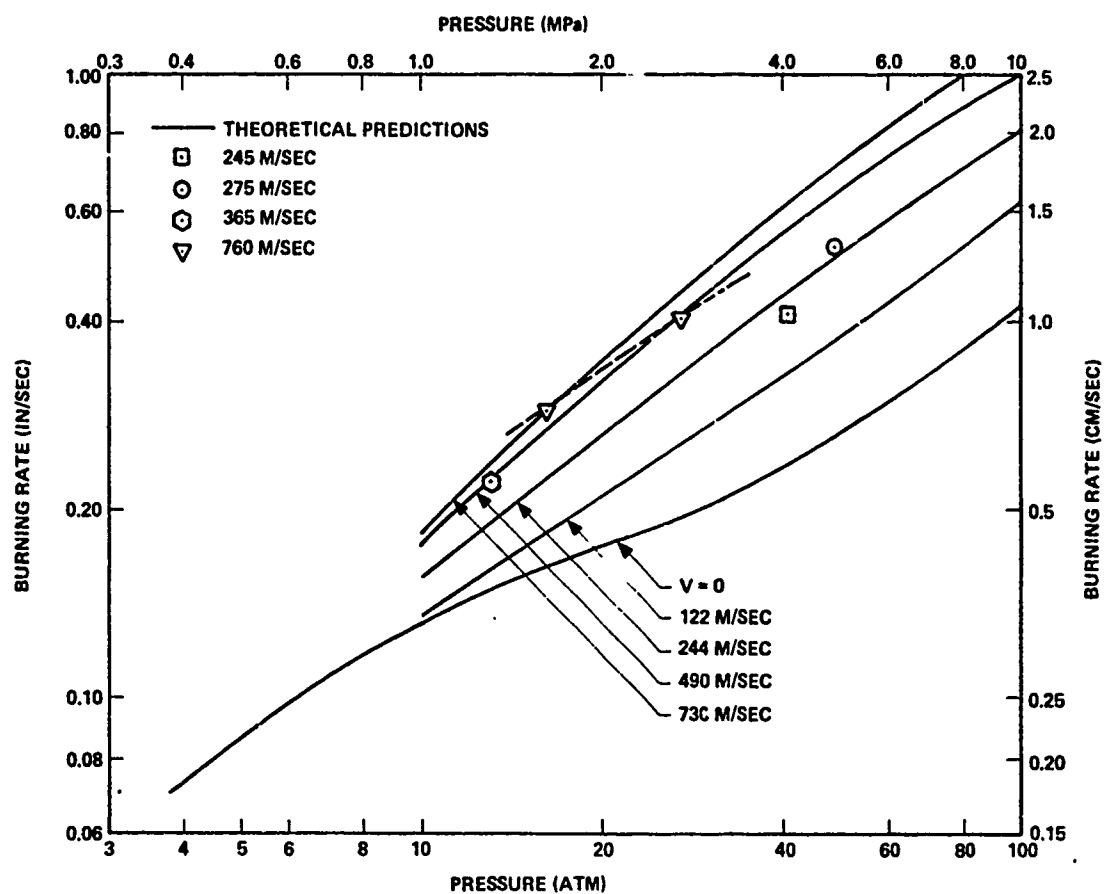


Figure 15. Theoretical and Experimental Burn Rate - Pressure Relationships for Various Crossflow Velocities for Formulation 6626 (2460°K Formulation, 74/21/5 AP/HTPB/AL).